# On the bridge: Asteroseismology meets nuclear astrophysics in massive stars

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# Key ingredients for nucleosynthetic yields

There are three key “ingredients” to nucleosynthetic yields:

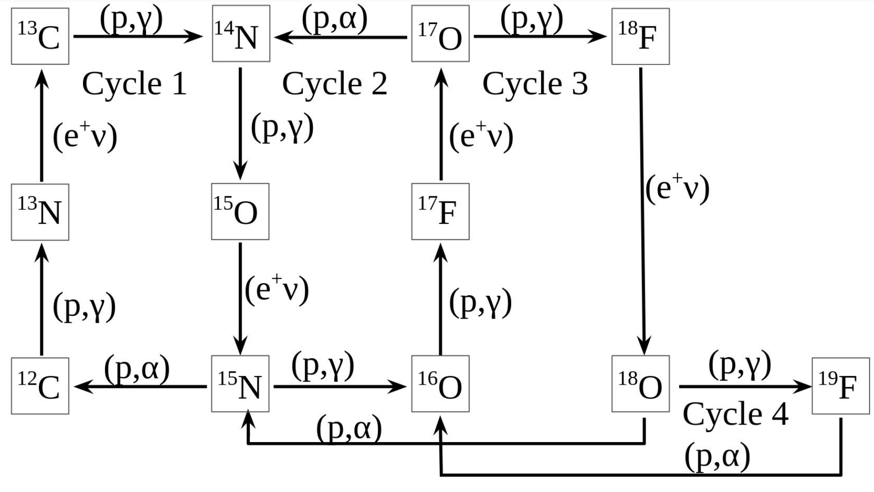
- ❑ How to produce the isotopes?
- ❑ How to move the isotopes inside the star?
- ❑ How to move the isotopes out of the star?

These come together in massive stars

# How to produce the isotopes?

Nuclear reaction rates:

- ❑ Control isotope production and their ratios
- ❑ Duration of burning cycles
    - ❑ Lifetime of the star




Project input:

- ❑ 212 isotope nuclear network
- ❑ JINA reaction-rate library

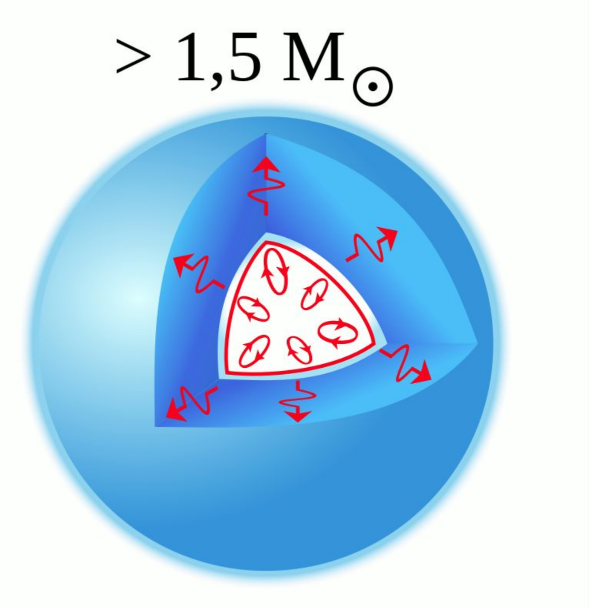
# How to move the isotopes inside the star?

Mixing processes:

- ❑ Convective boundary mixing
- ❑ Envelope mixing

Project input:

- ❑ Ledoux criterion for convection
- ❑ **Asteroseismically inferred values for convective boundary mixing and envelope mixing**



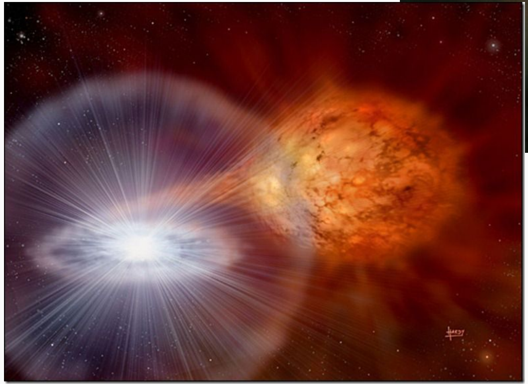
# How to move the isotopes out of the star?

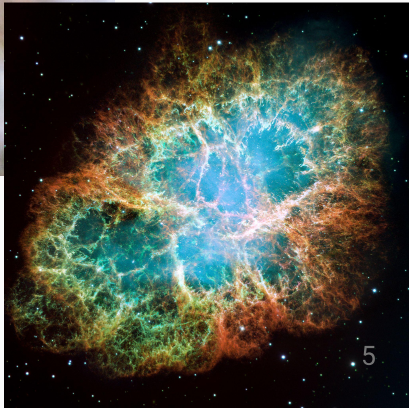
Mass loss via:

- ❑ Stellar winds
- ❑ Supernova explosions
- ❑ Binary interactions

Current project focus:

- ❑ **Stellar winds for wind yields**

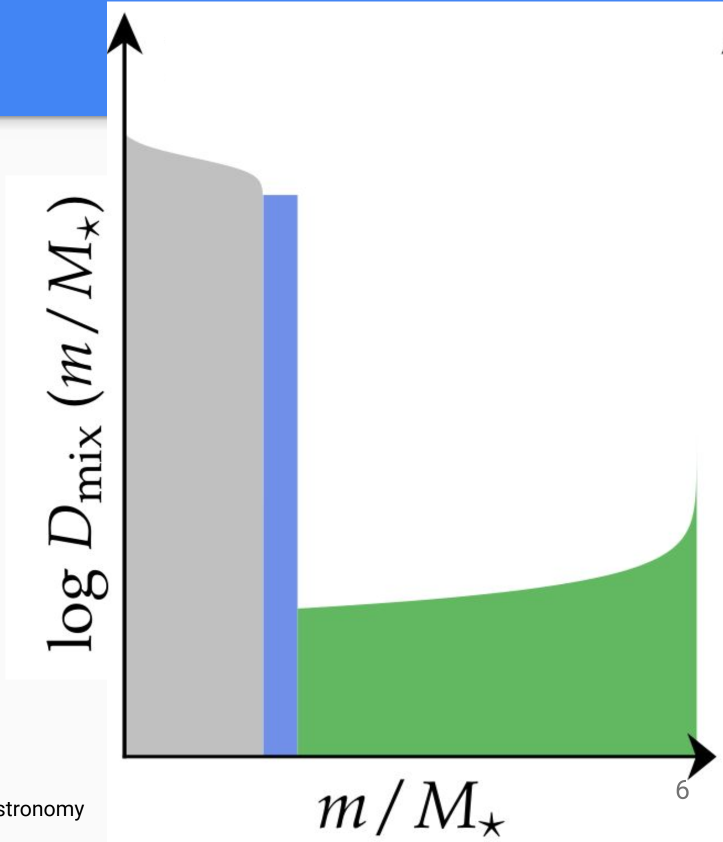




# Connection to asteroseismology

What is asteroseismology?

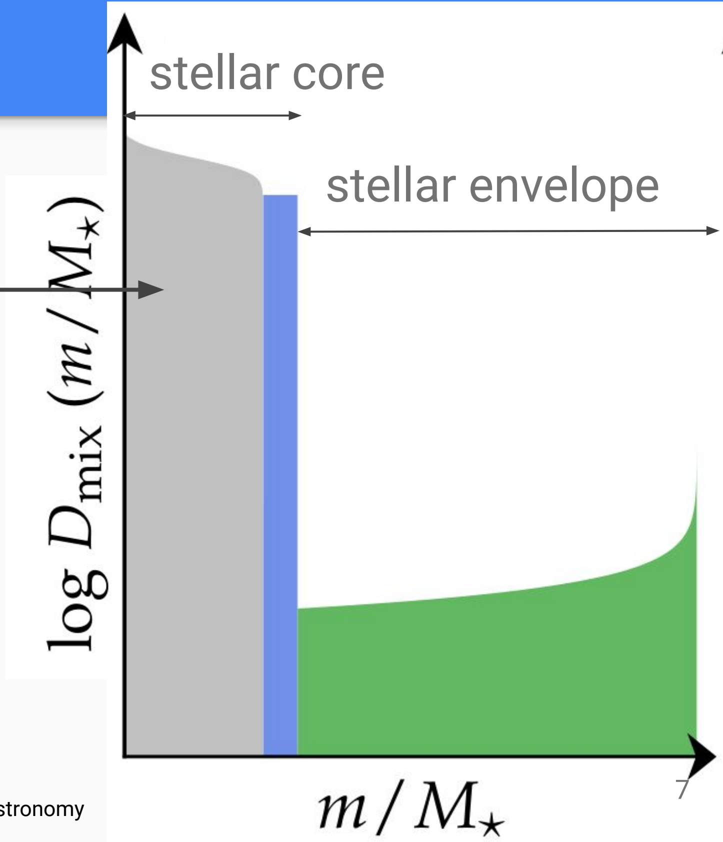
*Asteroseismology is the study of the internal structures of stars by means of their oscillations, comparable to how we learn about the interior of the Earth by studying earthquakes*




Pedersen, M. G.et al., 2021, Nature Astronomy

# Connection to asteroseismology

*Based on observations, stars have larger convective cores than standard stellar evolution models currently predict*

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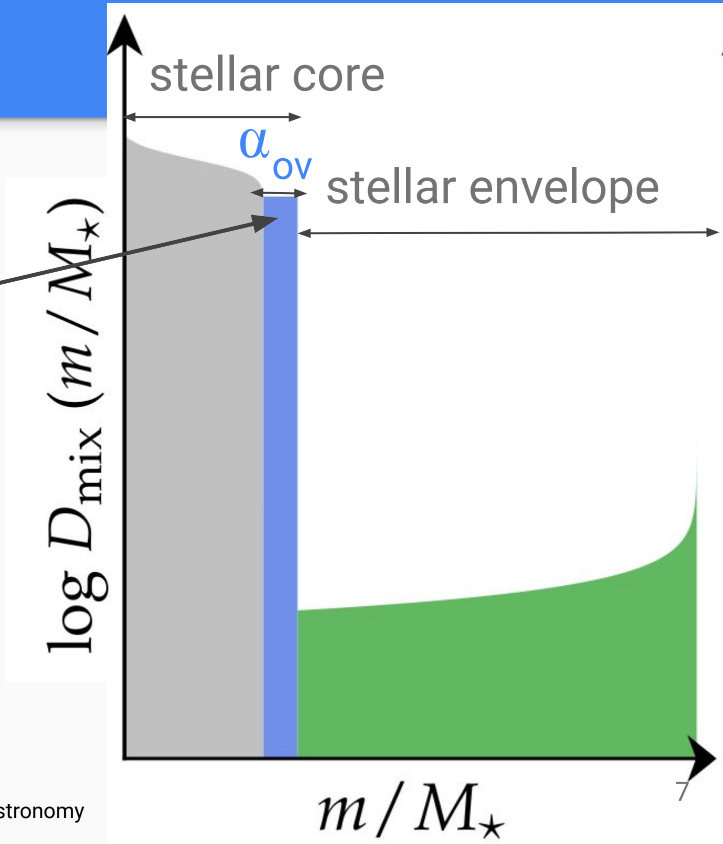
# Connection to asteroseismology

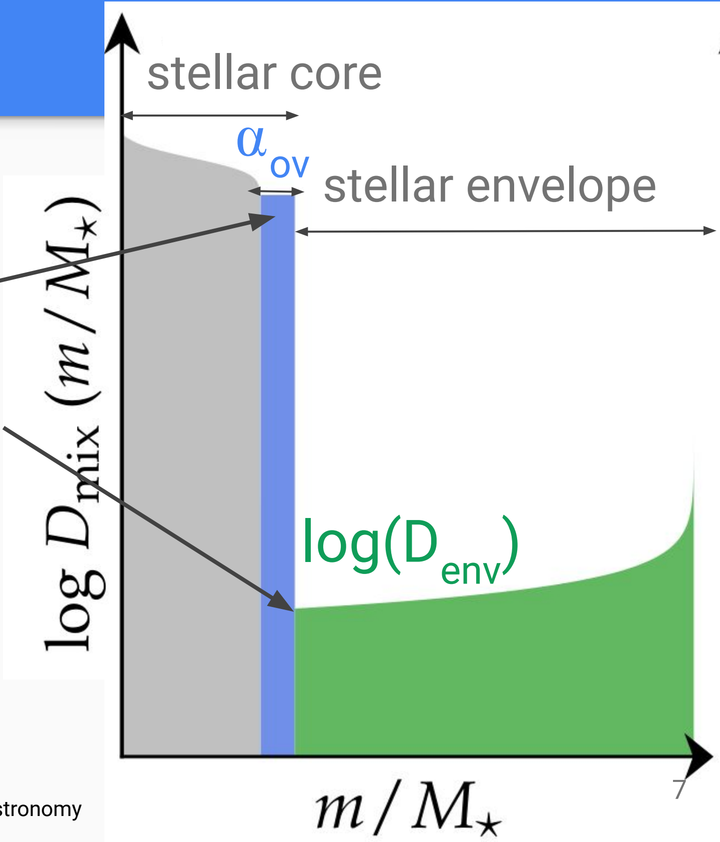
- How could this difference be solved?
  - Use of calibrated convective boundary mixing (CBM)




Pedersen, M. G.et al., 2021, Nature Astronomy

# Connection to asteroseismology

- How could this difference be solved?
  - Use of calibrated convective boundary mixing (CBM)
  - Use of calibrated envelope mixing (Denv) at the bottom of the envelope

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# Linking back to nucleosynthesis

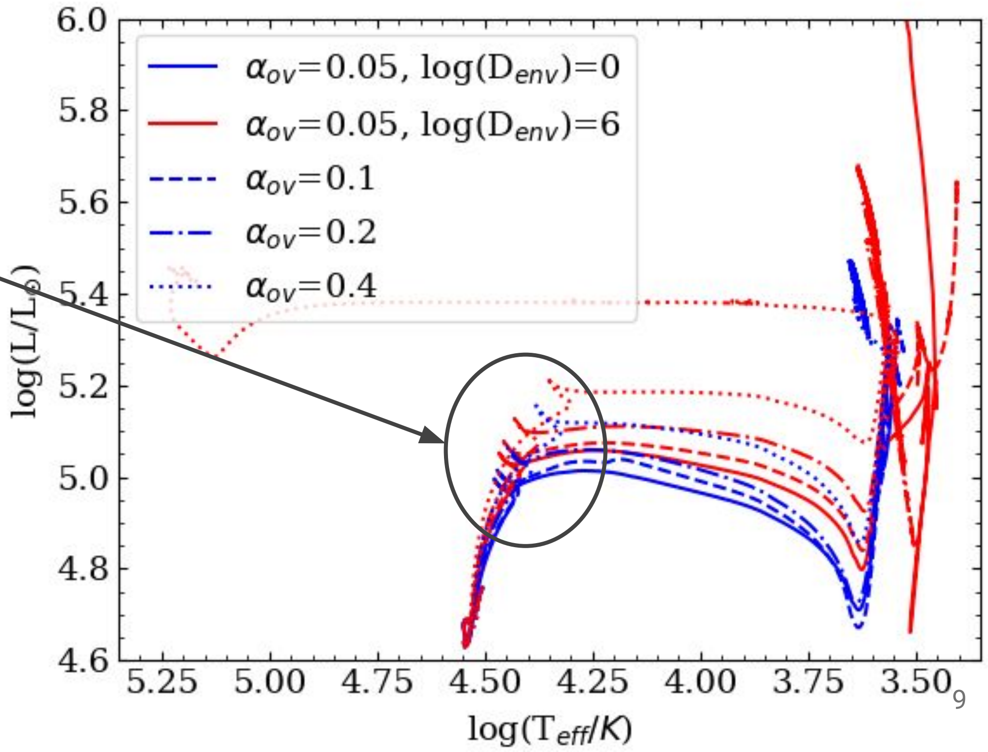
- Model ingredients:
  - Initial masses 7-30 $M_{\odot}$, covering the lower and upper supernova boundary
  - Initial metallicity Z=0.014
  - Nuclear network of 212 isotopes
  - $\alpha_{ov}$ and $D_{env}$ are varied according to asteroseismology

# Linking back to nucleosynthesis

- Model ingredients:
  - Initial masses 7-30 $M_\odot$, covering the lower and upper supernova boundary -> **Starting with 20 $M_\odot$**
  - Initial metallicity Z=0.014
  - Nuclear network of 212 isotopes
  - $\alpha_{ov}$ and $D_{env}$ are varied according to asteroseismology

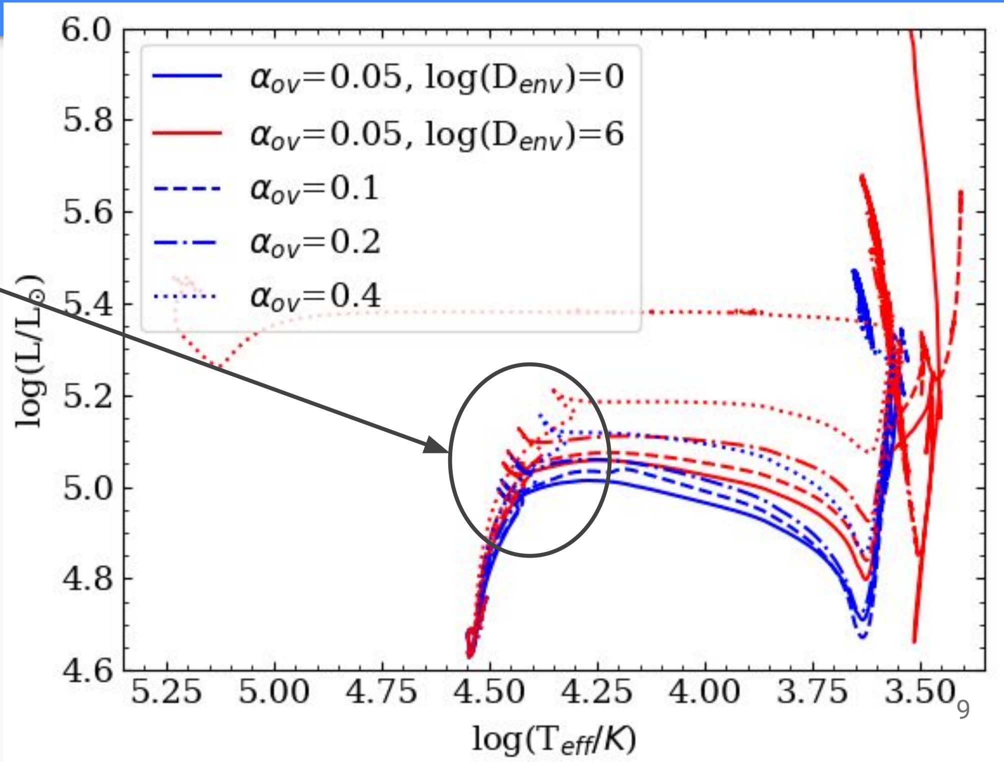
# Linking back to nucleosynthesis, first tests

- More CBM/a higher Denv leads to:
  - <u>Higher luminosity</u> at the TAMS
  - 4.98 - 5.22 $\log(L/L_\odot)$



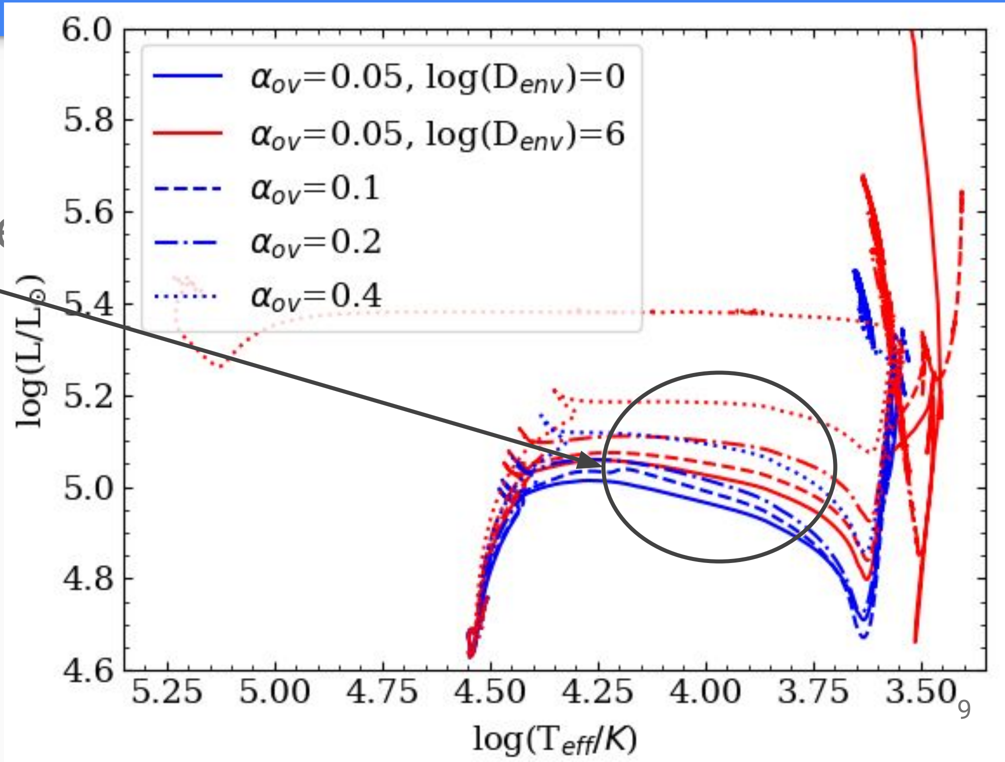
# Linking back to nucleosynthesis, first tests

- More CBM/a higher Denv leads to:
  - Lower temperature at the TAMS
  - 4.36 - 4.46 $\log(T_{eff}/K)$



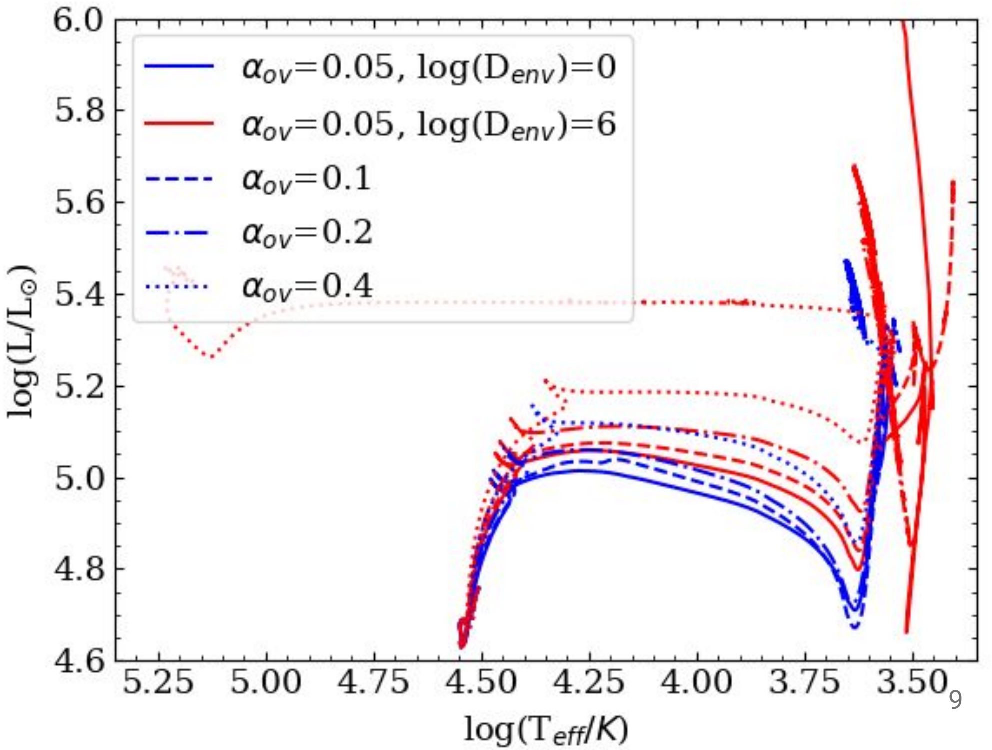
# Linking back to nucleosynthesis, first tests

- More CBM/a higher Denv leads to:
  - <u>Higher luminosity</u> on the Hertzsprung-gap
  - 5.06 - 5.33 $\log(L/L_\odot)$



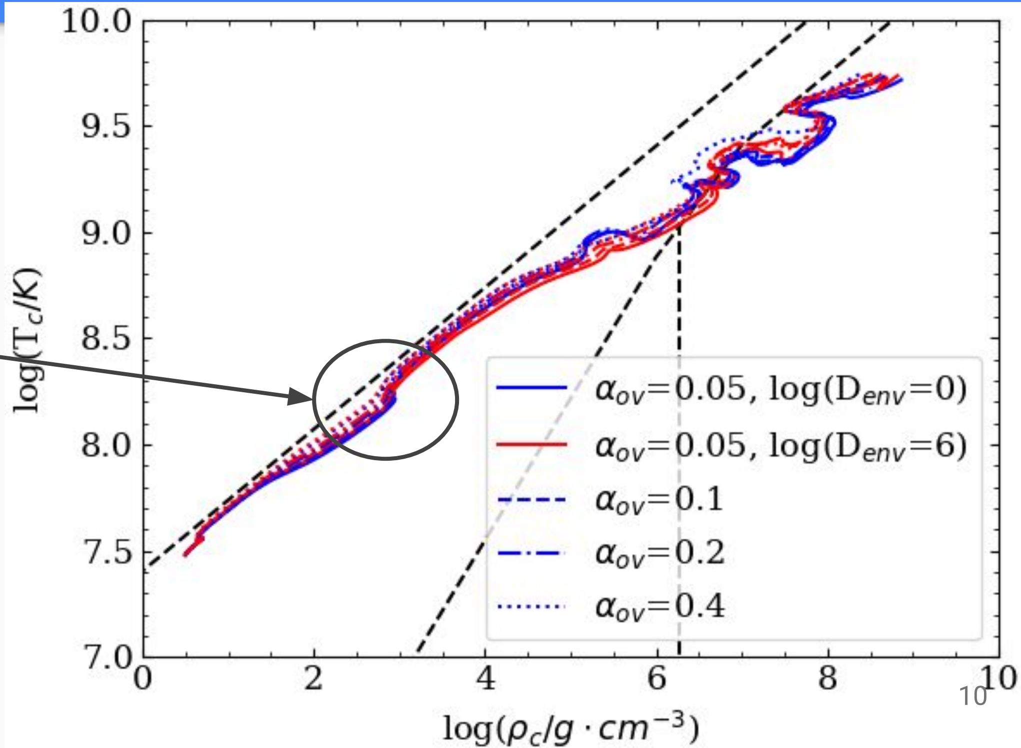
# Linking back to nucleosynthesis, first tests

- More CBM/a higher Denv leads to:
  - <u>Longer duration</u> of the main-sequence
  - 8.08 - 10.13 Myr



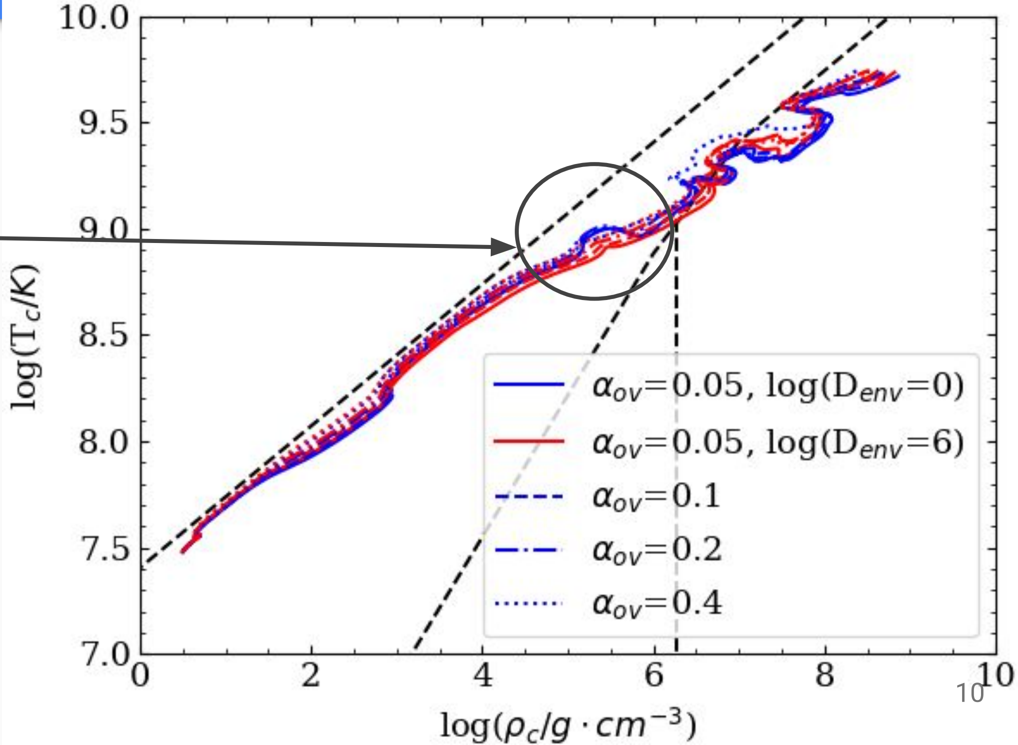
# Linking back to nucleosynthesis, first tests

- More CBM/a higher Denv leads to:
  - Higher central temperature at helium burning
  - 8.24 - 8.27 $\log(T_c/K)$



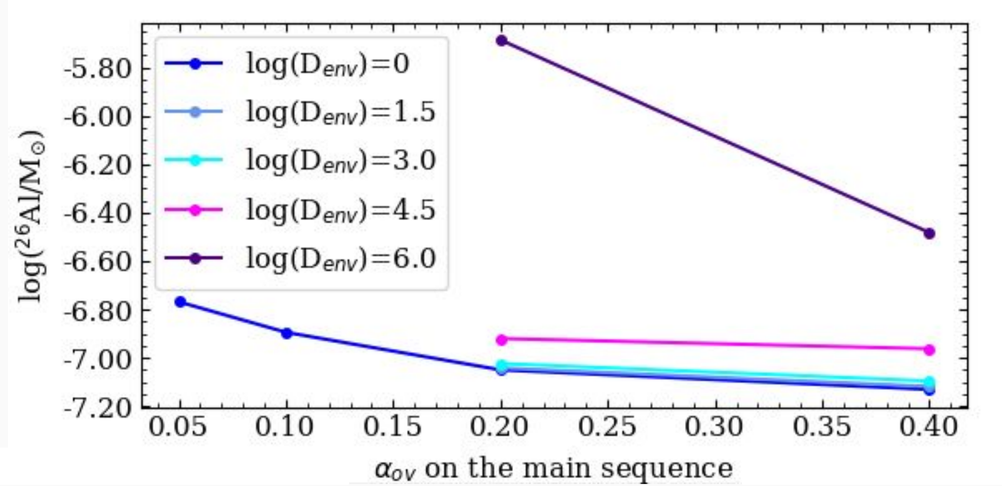
# Linking back to nucleosynthesis, first tests

- More CBM/a higher Denv leads to:
  - An earlier transition to radiative carbon burning



# Linking back to nucleosynthesis, first tests

- More CBM leads to:
  - a lower $^{26}$Al yield -> longer main-sequence leading to more internal decay
  - 8.08–9.49 Myr
- A higher Denv leads to
  - a higher $^{26}$Al yield -> more mixing within the stellar envelope



# Future work

Full set of models coming, stay tuned!

- Future work will include:
  - Complete nucleosynthetic wind yields
  - Details of the evolution of the stellar models, such as:
    - Lifetimes,  total and for separate burning phases
    - Mass loss, total and for separate burning phases
    - Core masses
    - C/O-ratio for the helium-depleted cores